# Wind divergence - rainfall relationships in 9919 hours of tropical single Doppler radar data

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*Monthly Weather Review*

Submitted March 2004

# ABSTRACT

A simple new analysis for large single-Doppler radar data sets is presented and illustrated using data from COARE, TEPPS, EPIC, JASMINE, SCSMEX, KWAJEX, and LBA field experiments. A cylindrical grid is used, to respect both the geophysical importance of height and the radar importance of range and azimuth. Horizontal and temporal fine structure are sacrificed, as data are binned into histograms in each region of $15^{o}$ azimuth x 8 km range x 500 m height x 1 hour. Mean Doppler radial velocity in each region is also carried. Later this velocity is de-aliased using a histogram method and fed into a Velocity-Azimuth Display (VAD) analysis, which yields profiles of horizontal wind divergence for circles of different radii centered on the radar, along with a mean wind profile. The VAD results, viewed in the context of statistical reflectivity characterizations, appear to contain useful information in many weather situations, not just occasional widespread or heavy rain events.

Statistical results from several radar deployments are shown, in the form of linear regressions of divergence at each altitude versus reflectivity-estimated surface rainrate. In all cases, low-level convergence and upper-level divergence accompany rain of course, but the profiles have some interesting shape differences, indicative of different heating profiles. Since the absolute magnitude of divergence-per-unit-rainrate profiles is physically constrained by a moisture budget, this analysis provides a new, independent check on reflectivity calibration, within the uncertainties in Z-R rainrate estimates and other assumptions. Results agree well with other calibration methods. Time-lagged regression analysis shows a characteristic evolution which is similar all around the world: convergence at low levels leads precipitation by one to several hours, then ascends to the middle troposphere at positive lags of a few hours.

## 1. Introduction

Scanning Doppler weather radars produce large data sets containing unique and valuable information on air motions and precipitation processes on scales of kilometers to 100s of kilometers. Extracting the information systematically is not simple, however, because radars measure unusual quantities in awkward antenna-centric coordinates, conditional upon the presence of sufficient scatterers. This article describes a new method for processing large volumes of single-Doppler radar data into a user-friendly form for statistical studies.

The scientific goals of this project call for reliable, robustly-sampled observational data on the relationships among convective cloud amount and vertical structure (as inferred from radar echo), area-averaged wind divergence (from the Doppler velocity data), and thermodynamic structure (from local balloon soundings). The motivation is that these relationships are relevant to the problem of parameterizing convection in coarse-resolution atmosphere models. In particular, wind divergence profiles are strongly related to heating profiles (Houze 1982, Johnson 1984, Mapes and Houze 1995), an important factor in large-scale tropical dynamics (e.g. Hartmann et al. 1984; Cho and Pendlebury 1997; Lin et al. 2004). This analysis extends earlier works of Mapes and Houze (1993, 1995), where targeted sampling by airborne Doppler radars meant that the results were specific to the mature stages of highly vigorous and organized mesoscale convective systems. By applying similar techniques to all-weather data from surface-based radars, we can obtain robust results extending to a much wider range of precipitating weather situations, including some with spotty and modest-depth convective clouds.

Every study using radar data must contend with the issue of sheer data volume. Information is necessarily lost in data reduction, and in this case we chose to sacrifice fine structure in the azimuthal direction and in time. For scientific reasons, we chose to preserve vertical structure as much as the measurements allow. We also chose to preserve dynamic range in reflectivity, in order to allow recalibration of the data in light of nonlinear relationship(s) between reflectivity and rain-rate. The point of mentioning these choices (which are detailed below) is to note that they differ from and complement other common uses of radar data like low-level echo mapping.

For clarity, the paper is divided into several short sections. Section 2 discusses the data pre-processing, where raw inputs are binned into a coarse space-time grid. Section 3 discusses our velocity unfolding strategy. Section 4 describes the Velocity-Azimuth Display (VAD) analysis from which we derive wind and wind divergence. Section 5 considers the trade-offs between random errors (noise) and coverage gaps, and describes strategies of pooling data in height and range. Section 6 shows example data for individual hours and time-height summaries from the EPIC 2001 experiment. Section 7 shows example statistics and illustrates one pre-scientific use of the results: obtaining an independent calibration estimate by equating reflectivity-derived rainfall and Doppler-derived moisture convergence estimates. Section 8 shows an example of scientific analysis: the time-lag between low-level convergence and precipitation. Section 9 gives a summary and indicates future scientific directions for the use of these data.

## 2. Space-time binning

Raw radar data are measured in a spherical[1] coordinate system centered on the antenna. Many radar analyses begin by remapping the data to a Cartesian grid, but this disguises real range-dependent aspects of the radar's sampling characteristics and makes the interpretation of

1. The downward refraction of radar beams by the atmosphere's vertical density gradient introduces a non-neglegible distortion. We apply a traditional approximate correction: the height of the beam above the earth's surface is as if the earth had 4/3 its actual radius.

radial velocity data awkward. We chose an option in between: a cylindrical grid (technically, a spherical cap since the earth is curved). In this approach, shown schematically in Fig. 1, a height coordinate is introduced for its special geophysical significance, while horizontal space is kept in polar (range-azimuth) form. In light of the importance of altitude, high resolution was retained: 500 m, roughly the width of a typical radar beam at the closest range where the beam samples the atmosphere quasi-horizontally (for example, a 1 degree beam is 500 m wide at 30 km range). To reduce data volume, we chose a coarse horizontal grid (with twenty-four 15-degree bins in azimuth, and twelve 8-km bins in range) and a coarse time discretization (hourly).

Since radar reflectivity is nonlinearly related to physical quantities of interest, such as rainfall rate, carrying simple averages in such coarse space-time bins would make no sense. Instead, the analysis carries in each spatial bin a histogram of all the values reported by the radar during the hour. Our reflectivity bins are every 1 dBZ, which is typically the full precision of the data. The histogram bins are numbered from 0 to 60. Since we care little about the exact value of very low reflectivity values, all detectable radar echoes below 2 dBZ are counted in bin 1. Whenever the radar reports no detectable echo, bin 0 is incremented by one count. Reflectivities over 60 dBZ (which are occasionally observed) are counted in bin 60. We also collect histograms of other measured quantities, such as Doppler spectral width and polarimetric quantities when available. To take fuller advantage of polarimetry requires more storage-intensive joint histograms, which is beyond the scope of the present paper. For spectral width, the histogram in each spatial bin covers the range from 0 to the Nyquist velocity $V_{nyq}$, in increments of 1 m $s^{-1}$.

For radial velocity, special considerations apply. The important quantity for our purposes is the mean radial velocity $V_r$ in each spatial bin, so a floating-point sum is continuously updated as data arrive in the input stream. This sum can be divided by the number of samples (sum over the $V_r$ histogram) to yield a true average. Histograms of $V_r$ are not geophysically meaningful as such, since they are only one component of the scatterers' motion vector, along the non-constant pointing direction of the beam. However, a histogram is needed for the dealiasing process (as described in the next section). For this purpose, crude resolution is sufficient, so we use 4 m $s^{-1}$ bins spanning the unambiguous velocity range from -1 to 1 times the Nyquist velocity $V_{nyq}$ (typically 10-20 m $s^{-1}$ in these data sets).

The pre-processing algorithm accepts an input stream of all data collected by the radar, without regard to the 2D or 3D context of sweeps or scans or volumes. As measured values at each range gate are read, their position in the antenna-relative grid is computed from the beam's elevation and azimuth angles and distance along the beam. Based on this location, each datum is used to increment the count in the appropriate histogram bin, and added to the cumulative sum in the case of a $V_r$ datum. When the value of UTC hour changes, the histograms and Doppler sums are written out in a file, the arrays are re-initialized to zero, and then processing continues. If the input stream ends, the histograms and sums are written out to a file. When the program starts anew, if the next input data are from a UTC hour for which a file already exists, the arrays are read in and the accumulation of new data continues until the end of the hour or end of input stream.

## 3. Doppler unfolding

Doppler measurements of $V_r$ have an inherent ambiguity arising from pulse-pair processing: it is impossible to distinguish whether scatterers have moved some whole number of radar wavelengths, in addition to any partial wavelengths, in one pulse interval. As a result, it is necessary to use supplementary data (such as space-time context or first guesses) to know whether the true value of radial velocity at a given point differs from the radar-reported $V_r$ value by +/- $2nV_{nyq}$, where n is an integer. For example, a recent paper describing strategies is Gong et al. (2003). Since the purpose of this project is to process and utilize large amounts of single-Doppler radar data, labor-intensive methods of editing input data are out of the question. This is where the $V_r$ histogram comes into play. Reference to the schematic $V_r$ histogram shown in Fig. 1 may be helpful to understand the strategy.

The first step in velocity unfolding is to account for the possibility that some of the $V_{nyq}$ samples in a given space-time bin are folded differently from others, as in the schematic Fig. 1. In essentially all of the weather situations sampled here, an hourly histogram of true radial velocity is narrow enough to have a clear central value. That is, the range of values occurring within an hour in a given spatial bin is comfortably smaller than $2V_{nyq}$. As a first step, we bring the suite of measured values of $V_r$ into a common range by finding the periodic array-shift of the Vr histogram which minimizes the variance of the distribution it depicts. In the split-histogram case illustrated in Fig. 1, we would assume that the block of negative $V_r$ values on the left side of the histogram should really be attached to the block of values on the right-hand end, representing a simple unimodal peak, since that interpretation minimizes variance. When some minority of the $V_r$ values are assumed to be folded (aliased) relative to the majority, the grid cell's mean $V_r$ value can be simply corrected by adding or subtracting $2V_{nyq}$ times the fraction of the values which are folded.

The second step in velocity unfolding is to decide whether the entire distribution of values needs to be adjusted by +/- $2V_{nyq}$. For this stage, we turn to a meteorological first-guess wind estimate. In most cases we have worked with, rawinsondes were launched from the radar site, so our first choice is to use those wind measurements, interpolated in time as necessary. When such local measurements are not available, data from the 6-hourly NCEP global reanalysis are interpolated in space and time to the radar location. In either case, a mean wind guess plus the beam geometry are sufficient to produce a first-guess radial velocity. The mean $V_r$ value is shifted upward or downward by $2V_{nyq}$ to make it closest to this first guess. Since $2V_{nyq}$ is typically 25 m $s^{-1}$, the first guess assumptions don't need to be highly accurate in order to meaningfully constrain this part of the unfolding process.

Some automatic quality control can be performed at this stage, by flagging as bad those values of grid cell-mean $V_r$ whose underlying histogram is too flat or too sparse. Flatness could be a problem if the wind fluctuations within an hour were large relative to $V_{nyq}$, or if the radar recorded Doppler values even when no significant power was measured. To screen for such problems, we require that the standard deviation implied by the $V_r$ histogram be less than 6 m/s. For the present we admit histograms consisting of as little as a single value, because noise or random error will drop out of statistical analyses which are our main concern (discussed further below). For individual-hour case studies a more stringent threshold could be applied. To optimize data use, we are considering how to formulate a continuous error estimate for mean $V_r$, based on the histogram, for use as a weighting function in an optimal harmonic fitting routine for the VAD analysis. Currently, all $V_r$ data passing the above quality thresholds are equally weighted in the fit.

## 4. Velocity-Azimuth Display (VAD) processing

After the two-step unfolding process described above, we have a value of mean radial velocity of the scatterers in each space-time bin. In order to estimate a mean horizontal wind and wind divergence at each altitude, an estimate of the component of $V_r$ contributed by vertical particle fallspeed is removed in order to isolate the horizontal component of radial velocity $V_{rh}$:

$$V_{rh} = \frac{V_r - V_t \sin\phi}{\cos\phi} \qquad (1)$$

Here $\phi$ is beam elevation angle and $V_t$ is a terminal fallspeed estimate, based on a relationship with reflectivity and air density (Lee et al. 2000). A sudden rain-snow transition in $V_t$ is assumed at the $0^{o}C$ level, in order to produce a characteristic profile kink as a tracer of the importance of this uncertain term. No attempt is made to account for vertical air motions. Our best Doppler VAD results, for this reason and others related to averaging, are for mesoscale circles using data from far enough away that the beam is quasi-horizontal, yet close enough that beam width and the height of the lowest beam are not too great.

The Velocity-Azimuth Display (VAD) method of Browning and Wexler (1968) is used to calculate wind and its divergence. An example calculation is illustrated in Fig. 2, with $V_{rh}$ values from a fixed range plotted versus azimuth angle (local navigation angle, measured clockwise from north). We have found that 24 azimuth bins of 15-degree width works well. With coarser azimuth bins, a significant error can arise from misattributing the angle at which the radial velocity applies. With finer bins, the problem of missing data can become more problematic and array size becomes larger.

A least squares harmonic fitting program is used to fit an azimuthal mean value and wave-number-1 sinusoid to all non-bad values of $V_{rh}$. Using the divergence theorem, the area-averaged horizontal wind divergence is computed as the azimuth-mean $V_{rh}$ multiplied by the perimeter-to-area ratio (2/R, where R is radius) for the circle in question. To the extent that our range bins are coarse (8km, or 24-40km in range-pooled data), the value of R is inexact (we take a value corresponding to the center of the range bin), yielding one source of error for the estimated divergence.

The phase and amplitude of the wave-1 sinusoid are indicative of the direction and strength of a mean wind. Since it makes little sense to have different mean wind estimates for circles of different radii, Vr data are first pooled for the ranges with the best geometry (32-72 km horizontal range) before the harmonic fit to yield a single wind profile. The uses of this wind profile are merely qualitative: we plot it alongside the first-guess wind profile and look for gross inconsistencies that might indicate unfolding problems. However, small systematic differences between this wind (which indicates flow in precipitation particle-containing regions) and a rawinsonde-measured wind (which is more likely a random sample, or slightly biased to clear air) might provide a glimpse of vertical momentum transport effects in convection.

More automatic quality screening is applied at this stage of the analysis. For sheer numerical reasons, the harmonic fit requires that $V_{rh}$ values be available at 4 or more azimuths. For reliability, it is desirable that the data span a wide range of azimuths, or more specifically that the largest angular gap with no data not be too wide. We borrow a practical definition of "too wide" from rawinsonde budget studies, whose results are usable even when only a triangle of wind soundings is available: here, wind and divergence estimates are discarded whenever the maximum data gap is more than 120 degrees in azimuth.

## 5. Pooling of data in range and height

Our desire for wind divergence profiles in a wide range of weather conditions is thwarted by the fact that the radars whose data are analyzed here don't measure Doppler velocity in clear air. This coverage problem manifests itself in missing values, especially in the upper troposphere. Missing values limit our ability to improve divergence profiles through mass-balance constraints, and integrate them vertically to get vertical velocity estimates for evaluating advection terms. Although data machinations cannot create information about an unmeasured quantity, we do want to tease all possible signals out of the data. For statistical analyses, we would rather have noisy estimates than none at all. Based on these considerations, it is sometimes helpful to pool the data from different original regions of our space-time grid into coarser spatial regions. The pooling procedure is straightforward: all histograms are simply added together, as are the floating-point $V_r$ sums.

For example, in order to increase the number of available divergence estimates at upper levels for the analyses presented here, the data are regridded from 500m height increments to 50 hPa pressure increments, with the correspondence based on a mean tropical sounding as illustrated in Fig. 3. For example, the pressure layer 200-150 hPa is seen to contain all the data ascribed to nominal heights of 12.75, 13.25, and 13.75 m, i.e. all measurements between 12.5 and 14 km, increasing the likelihood that the conditions necessary for a divergence estimate to be produced will be met. Of course, this procedure also increases some sources of error for that estimate. For example, if there is strong wind shear in this layer and the radar samples come from different altitudes in different directions from the radar, the shear will be aliased into apparent wind divergence due to this vertical data pooling. For statistically isotropic echo fields, like a radar on a ship at sea, this will be only a random error, but it could be a more systematic bias for, say, a coastal radar where echo height might have a systematic bias with respect to azimuth angle.

Data are also pooled in range to increase the number of possible divergence estimates. Centered pooling is used, with data in each 8km horizontal range bin augmented by data from one or two adjacent bins at closer and farther range. In this case, divergence error is introduced by increased ambiguity in the perimeter-to-area ratio 2/R, as discussed above. Again, this error is probably random for statistically homogeneous echo fields, so it is a worthwhile trade-off for our statistical studies to gain noisy estimates rather than have none.

## 6. Examples: individual hours and time-height summaries from EPIC 2001

The analysis described above has been performed on data from 12 deployments of research-quality Doppler radars in the tropics (Table 1), in the 7 locations indicated as solid squares on Fig. 4. Each deployment was different, but most were more than 20 days (480 h) in duration, for a total of 9919 hours in our present database. Most deployments sampled convection occurring over different parts of the Indo-Pacific warm pool, while the TRMM-LBA experiment in Brazil provided our only data over land.

An example of standard hourly analysis products is shown in Fig. 5, from the EPIC experiment in the tropical eastern Pacific, at 08 UTC on 24 July 2001 (decimal day 267.35). Low-level southerly winds suggest this hour was after the trough and before the ridge of the synoptic-scale easterly waves characterizing the weather of EPIC (Petersen et al. 2003, Raymond et al. 2004). Low-level zonal wind also turned to westerly during these southerly phases of the “easterly” waves (Fig. 8). The VAD example plot in Fig. 3 also comes from this hour’s data, at the level of 725 mb and a range of 48 km.

To roughly characterize the radar echo field, Fig. 5a shows a plan-view depiction of low-level echo, while Fig. 5b shows a contoured frequency by altitude (CFAD, Yuter and Houze 1995) diagram summarizing the vertical echo structure inside the 88 km range circle. The plan-view depiction has two parts: filled contours of the fractional coverage by detectable echo during the hour, and open contours (with a nonlinear contour interval, proportional to the square root) of rainrate R estimated from $R = aZ^b$, where Z is reflectivity and (a,b) = (228, 1.25, Hudlow 1979). A large region of very high fractional coverage and high rainrate is seen south-southeast of the radar, while partial coverage and lower rainrates characteristic of weaker echoes are seen to the north and west. The CFAD shows a broad distribution of reflectivities 0-40 dBZ in the lower troposphere, and 0-25 dBZ above the $0^{o}$C level (~550 hPa), with only a slight hint of a melting-level bright band.

The VAD products shown for this hour include mean wind (Fig. 5c) and wind divergence (Fig. 5d-f). Mean wind is southwesterly at low levels and northeasterly in upper levels, in general agreement with the rawinsonde-measured winds used as the first guess for Doppler unfolding (only in the uppermost troposphere were any Doppler velocities folded at this time). Winds were generally convergent below the 650 hPa level, and divergent at higher altitudes (Fig. 5d). Divergence averaged over the smaller circles (like 40 km radius, solid) tends to be larger in magnitude than that averaged over larger circles. In this case, convection with strong middle-level outflow (near 450 hPa) is indicated in the small circles, while the largest circle shown (88 km radius) has its divergence at higher altitude, up to 200 hPa. We deduce that vigorous growing convection of middle height was occurring near the radar, while some of the farther-out heavy rain areas indicated in Fig. 5a contained deeper convection. Since echo coverage is abundant in this case, VAD divergence computed from range-pooled data (Fig. 5e,f) looks very similar to the unpooled, but smoother and hence perhaps easier to appreciate at a glance.

The situation 6 hours later is shown in Fig. 6. At this stage, the radar echo is mostly to the northeast of the radar (Fig. 6a), with the large smooth area of high fractional echo coverage indicating stratiform precipitation. This interpretation is supported by Fig. 6b, in which high reflectivities in the upper troposphere are less numerous relative to Fig. 5b, consistent with reduced lofting of large particles by convective updrafts. The melting-level bright band at 550-600 hPa, typical of stratiform precipitation, is distinct in Fig. 6b. The divergence profiles (Figs. 6d-f) are similar in shape at all ranges, but again decrease in magnitude with radius as more and more clear-air and weak-echo regions are included in the circular area average. A classic stratiform divergence profile (Houze 1997) is evident, with convergence in middle levels and divergence in the upper and lower troposphere. In addition, an intense zig-zag pattern centered on the $0^{o}$C (550 hPa) level is seen, evidently the “melting mode” noted and discussed by Mapes and Houze (1995). Note that meridional wind v has a distinctive kink at that level, evident in the rawinsonde as well as radar data (Fig. 6c), supporting the robustness of these observations.

As a counterpoint to these vigorous weather situations, Fig. 7 shows the same figure for a calm period 10 hours later with little convective activity: 00 UTC on 25 September, 2001 (decimal date 268.0). At this stage, there are only some isolated echoes to the far north of the radar with little appreciable precipitation (Fig. 7a). The CFAD shows some low reflectivity echoes in the upper troposphere (Fig. 7b), perhaps the remnants of the stratiform anvil clouds from in Fig. 6b, with a melting-level bright band and a bit of light rain down to the surface. Consistent with the absence of convective activity, the divergence profiles are close to zero, although some structure near the melting level can still be seen (Fig. 7c, 7d).

Time-height sections summarizing the EPIC 2001 radar data set as a whole are shown in Fig. 8. The upper panel (Fig. 8a) indicates fractional coverage by detectable echo, overlain by a Z-R near-surface rainrate estimate as a heavy curve. Frequent episodes of precipitation are seen, with echo extending to about 150 hPa or 15 km in most cases, and a distinct enhancement of echo coverage at ~300hPa (~9 km) occurred at various times throughout the 20-day period (Zuidema and Lin 2003). Figure 8b shows the maximum azimuth gap with no valid Doppler Vr estimates in the 40-48 km range annulus. Surprisingly, there is abundant Doppler data at all times, even near the tropopause - a peculiarity of the EPIC data, for which the screening parameters on the radar's data system were apparently set to be unusually generous. Many of the $V_r$ histograms in clear conditions contain only a single Doppler value, but again for statistical analyses a noisy estimate is better than none. The possibility that these occasional Doppler velocity estimates actually contributed valuable information is supported by the reasonable VAD winds in Fig. 8, approximate mass balance in Fig. 9, and near radius invariance of panel 9a (discussed further below). Could there be occasional stray ice crystals providing real backscatter, only to have that information usually (though not in EPIC) discarded by despecklers and other filters on the radar's data system?

Divergence (Fig. 8f) shows strong signals during times of intense convection, and weak speckled structure at other times, consistent with theoretical expectations that divergent flow is weak in the absence of intense diabatic heating -- but also with the simpler null hypothesis that the radar is simply seeing noise when no strong precipitation echo is present. The VAD-derived winds are highly consistent with the rawinsonde and reanalysis data (Fig. 8c,8d). Of course the latter were used as first guesses in the +/- $2V_{nyq}$ unfolding of the cell-mean $V_r$, but this is a very weak and often nonexistent influence, especially for the relatively weak winds of the EPIC domain.

## 7. Example statistics and radar calibration by Doppler moisture budget

The 432 hours of data indicated in Fig. 8 are easily small enough to read into computer memory, inviting statistical explorations. An interesting first statistic is simply the time-mean divergence (Fig. 9a). A general pattern of lower-level convergence and upper-level divergence is seen. Estimates from the smallest circles have a significant dependence on our fallspeed assumptions, as indicated by strong divergence indicated in the 575 and 625 hPa bins. This divergence certainly contains a large, known error from our assumption of pure raindrop fall speeds there: in stratiform rain, the high reflectivity in these layers is really that of wet aggregated snowflakes (see the bright band in Fig. 6 for example). On the other hand, sharp wind divergence structures do exist near the melting level (as seen in airborne Doppler radar data, with nearly horizontal beam geometry, by Mapes and Houze 1995). Rather than try to smooth over this artifact, we value it as a convenient indicator of fallspeed uncertainty, and note that it fades nicely with range. There is also a mild range dependence to the general convergence-divergence profile. Since smaller circles have more intense divergence signals during major rain episodes, as in Figs. 5 and 6, some radius dependence is expected to persist in simple time averages because the availability of divergence estimates is biased toward such episodes. Since ship position is arbitrary, a well-sampled climatological average should be radius independent.

Another notable feature of Fig. 9a is enhanced convergence in the lowest 1km. This feature is strong in EPIC and not prominent in many of our other datasets, consistent with regional divergence profile differences in both NCEP and ECMWF reanalyses (not shown). It may reflect genuinely broad-scale boundary-layer convergence, outside of deep convection, driven by the sea surface temperature pattern (Lindzen and Nigam 1987). This interpretation is further supported by the fact that it remains prominent in the residual of linear regressions relating wind divergence to convective echoes, as discussed next.

In order to more effectively isolate the divergence signature of precipitating convection, Fig. 9b shows profiles of the linear regression coefficient relating divergence at each height to near-surface precipitation estimated using the Hudlow 1979 Z-R relation. Both quantities are averaged over identical circular areas of varying radii. Radius dependence is very weak in Fig. 9b, consistent with the physical expectation of a linear relationship, as the greater variability of convection on smaller scales is common to both precipitation and divergence and hence drops out of the regression. Convergent flow extends almost uniformly up to 350-400 hPa, with a hint of extra-strong convergence at ~450 hPa, then divergence prevails up to 100 hPa.

A simple average over the 8 radii shown in Fig. 9b is shown as a solid line in Fig. 10d, along with identically-derived curves for many other radar deployments, all on a common axis. All show the qualitatively unsurprising result of low-level convergence and upper-level divergence being correlated with precipitation, although there are interesting subtleties to the different profile shapes, deserving of further study. A more striking aspect of Fig. 10 is that the profile amplitudes differ rather dramatically from one deployment to the next. The main reason for this is that absolute reflectivity calibration is quite variable, affecting precipitation estimates by factors of 2 or more through the nonlinearity of Z-R relationships (which also vary, but less so).

Figure 10 suggests a new approach to radar calibration, since the VAD-derived Doppler divergence profiles are completely independent of absolute values of reflectivity. Precipitation is physically related to wind convergence through heat and moisture budget considerations. The latent heating implied by a given precipitation rate is about equal to the dry static energy export implied by the wind divergence profile, to the extent we can neglect (or account for) the precipitation-correlated component of radiative heating, horizontal temperature advection, and local rate of temperature change. Alternately, precipitation minus surface evaporation is about equal to moisture convergence, which we estimate as the simple product of a time-mean humidity profile (75% relative humidity for a mean tropical temperature sounding from NCEP reanalysis) times the regression-derived divergence profiles of Fig. 10. In either case, these physical considerations are sufficient to meaningfully constrain the gross differences seen in Fig. 10's solid lines.

Table II shows calibration corrections (expressed as an additive dBZ offset) estimated using the moisture-budget approach and the data of Fig. 10. Calculations have been repeated for a common Z-R relation (Hudlow 1979), and for Z-R relations specific to the various projects (as indicated by references in the table). Since the Z-R relations in individual projects may have been fitted assuming a particular reflectivity calibration, their use complicates interpretation. Nonetheless, some results are clearly significant above and beyond this Z-R relation uncertainty. For example, data from the third MIT radar deployment of TOGA COARE experiment have a bias of nearly 10 dBZ, while the EPIC data indicate a very small bias. These offsets are in general agreement with other estimates (Table II). This consistency increases confidence in all methods, since the present Doppler method is completely independent of other reflectivity-based methods, such as metal-sphere calibrations in the field, solar-source calibrations, or comparisons with non-radar rain estimates.

## 8. Scientific analysis: the lag between low-level convergence and precipitation

Time lags between low-level wind convergence and deep convection are of interest both for the general interpretation of observations, and for theories of tropical dynamics (e.g. Emanuel 1993, Chao and Deng 1997). Reliable, statistically significant observational estimates of this time lag have been difficult to obtain, since the commonly-used sounding-array budget method has a temporal resolution of, at best, 3 hours (e.g. Cho and Ogura 1974, Song and Frank 1983). The current hourly time series of reflectivity and divergence can address the question, although interpretation is complicated by microphysical lags involving precipitation particle development and fallout, and by the role of advection in the Eulerian time sections analyzed here.

Recalibrated, range-averaged regression coefficients between divergence and precipitation are shown in Fig. 11 for eight radar deployments. The dashed lines on Fig. 10 correspond exactly to the vertical structure in the panels of Fig. 11 at lag = 0. Wind convergence (shaded) shows a characteristic phase tilt over several hours, rising from the lower troposphere ahead of the rainfall to the middle troposphere afterward: a familiar pattern in mesoscale convective systems, in which clouds evolve from convective to stratiform (e.g. Houze 1997). The present results lend further statistical weight and geographical generality to the finding (e.g. Rickenbach and Rutledge 1998, Nesbitt and Zipser 2003) that mesoscale systems, with characteristic time scales of hours, are a dominant contributor to total tropical rainfall. At the lowest levels, maximum convergence often occurs at a lead time of 1 hour, although the results are somewhat noisy. Low-level convergence (and associated shallow convection) may pre-condition the atmosphere for deep convection through moistening and/or cooling effects, as seen for instance in similar regressions of precipitable water estimates from a ship-based microwave radiometer in EPIC (not shown).

## 9. Summary and future directions

The analysis describes here reduces vast single-Doppler radar data sets to manageable size, opening new doors to convenient, systematic extraction of statistical information about precipitating weather systems on the radar-sampled mesoscale. Doppler data have been shown to be a useful constraint on the perennial problem of absolute reflectivity calibration. Scientific harvesting of the results of these analyses has just begun. There may be much to be learned from the differences among different deployments in different seasons and regions (Figs. 10, 11), although sampling issues are substantial even for these radar deployments of weeks to months in duration.

One next step in statistical analysis is to extend the simple linear regression technique of section 8 to a multiple linear regression (MLR). MLR can objectively tease apart the divergence signals associated with several different aspects of the cloud field, such as shallow and deep convection and stratiform precipitation. Preliminary tests using time series of rainfall from these different precipitation types, derived from convective-stratiform reflectivity separations, show that MLR returns sensible divergence profiles for each (not shown). Such statistical results may be useful for the estimation of heating fields using only reflectivity as an input (e.g. Cartwright and Ray 1999, Tao et al. 2000, Shige et al. 2002). Statistical relationships with auxiliary data such as balloon soundings may provide valuable data to improve cumulus parameterization schemes.

In addition to such broad-brush statistical analyses, this analysis technique may be useful for studies of particular types of weather (such as ordinary vs. hurricane-related rainfall), or even of particular cases. Individual-hour VAD wind and divergence profiles may often be good enough to derive usefully accurate estimates of large-scale advection terms, especially when combined with sounding, top-of-atmosphere, and surface measurements in variational analyses (Zhang and Lin 1997, Lin and Mapes 2004).

In future deployments, generous settings for speckle filters in radar data-collection systems, as apparently used in EPIC (Fig. 8), appear to be useful for this analysis and cost little or nothing. At worst, some random noise is included; at best, VAD measurements may become feasible for subtle effects such as clear-air boundary-layer convergence, and column mass balance may be improved. The vertical resolution of these analyses is markedly improved by a rich diversity of antenna elevation angles (for example, interleaved tilt-angle sets in successive volume scans within the same hour), again with minimal impact on traditional applications of the data.

We would like to build up an even larger open-access database from many more radars worldwide. The most efficient means would seem to be via distributed efforts, like gradual processing at archive centers or running the histogram-collection pre-processing in real time on operational data streams. We are currently working to read real-time data from some of the WSR-88D radars running continuously across the Unites States, available through the CRAFT project (Droegemeier et al. 2002). The data preprocessing and analysis codes are available upon request, along with data sets described here. Interested parties are encouraged to contact us or visit the project web site at http://www.cdc.noaa.gov/~jlin/radar/.

## Acknowledgements

This research was supported by National Science Foundation grant ATM-0097116. The work described here was made possible by the generous assistance and advice of Stacy Brodzik, Larry Carey, Kelvin Droegemeier, Grant Gray, Mircea Grecu, Paul Hein, Robert Houze, Steve Nesbitt, Steve Rutledge, Carl Sinclair, Jian-Jian Wang, and David Wolff, Sandra Yuter, and Paquita Zuidema. The excellent free Radar Software Library, written and maintained by the Tropical Rainfall Measuerment Mission (TRMM) Satellite Validation Office at NASA/GSFC, formed the invaluable basis for our analysis of data in so many different original formats.

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## Figure captions

Figure 1: Schematic depiction of the cylindrical coordinate system, and the histograms in each space-time grid cell.

Figure 2: Radial velocity (stars) along 48 km range circle at 725 mb measured by ship-borne radar during 0800-0900 UTC, 24 September 2001, during the EPIC project. The solid curve shows a fitted curve truncated at the first harmonic, and the dashed line shows its azimuthal mean.

Figure 3: Height and pressure coordinates used in this study.

Figure 4: Locations of the field experiments whose data are used in this study.

Figure 5: An example of the standard hourly data analysis product from the EPIC experiment at 08 UTC on 24 July, 2001 (Julian date 267.4). (a) A plan-view depiction of low-level echo. The filled contours are the fractional coverage by detectable echo during the hour, while open contours depict (with a nonlinear contour interval, proportional to the square root) estimated rain-rate R. (b) A contoured frequency by altitude (CFAD, Yuter and Houze 1995) diagram summarizing the radar echoes within the 88 km range circle. At each altitude, the indicated frequency in all the 1dBZ bins sums to the total fractional cover by detectable ("nonzero") echo at that altitude. (c) Mean wind profiles including first guess zonal wind (thin solid) and meridional wind (thin dash), and radar zonal wind (thick solid) and meridional wind (thick dash). (d) Divergence profiles averaged over circles of indicated radii. (e) As in (d) except for 3-range pooled data. (f) As in (d) except for 5-range pooled data.

Figure 6: As in Fig. 5 except for 14 UTC on 24 July, 2001 (Julian date 267.6).

Figure 7: As in Fig. 5 except for 00 UTC on 25 July, 2001 (Julian date 268.0).

Figure 8: Time-height sections summarizing the EPIC 2001 radar data set. (a) Fractional coverage by detectable echo < 96km from radar (contours: 1%, 31%, 61%, 91%), overlain by a near-surface area-averaged rainrate estimate (heavy curve, maximum value 6 mm $h^{-1}$). (b) The maximum azimuth gap with no valid Doppler Vr estimates at 44 km range (contour: 30 degrees, essentially all of domain is less than that). (c) Radar zonal wind (contours +/- 2,6,10...m/s, negative dotted and shaded). (d) First guess zonal wind, contours as in (c). (e) Radar meridional wind, contours as in (c). (f) VAD divergence at 44 km range (contours +/- 25,75,125...x $10^{-6}$ $s^{-1}$, negative dotted and shaded).

Figure 9: Statistics of 432 hours of data during the EPIC experiment. (a) Time-mean VAD-estimated divergence profiles. (b) Profiles of the linear regression coefficients relating divergence at each altitude to Z-R estimated near-surface precipitation.

Figure 10: Profiles of the range-averaged linear regression coefficients relating divergence to Z-R estimated near-surface precipitation for (a) TOGA COARE, first deployment of the MIT radar aboard the R/V *Vickers*, (b) TOGA COARE, second MIT/Vickers deployment, (c) TEPPS, (d) EPIC, (e) LBA, (f) Kwajalein, (g) JASMINE, and (h) SCSMEX. The solid curves are with original reflectivity values, while dashed curves are after reflectivity correction (additive in dBZ) based on equating precipitation and moisture convergence estimates. Range averaging is a simple mean over the 8 ranges shown in Fig. 9.

Figure 11: Range-averaged reflectivity-corrected regression coefficients, exactly like dashed curves in Fig. 10, but for different time lags of divergence with respect to precipitation.